Indian J. Phys. **66B** (5 & 6), 673 – 684 (1992)

A new method for evaluation of electron temperature in transverse and axial magnetic fields in an arc plasma

S N Sen
Department of Physics, North Bengal University,
Darjeeling-734 430, North Bengal, India

Abstract : The diffusion voltage in a mercury arc plasma has been measured for arc current varying from 2.5 A to 5 A in presence of transverse and axial magnetic fields varying from zero to 1.1 kilo Gauss. By assuming the radial distribution function of charged particles as proposed by Ghosal *et al* (1978) and utilizing the method introduced by Sen *et al* (1983), the ratio of electron temperature with and without magnetic field has been evaluated. It is found that electron temperature becomes a maximum in axial magnetic field and then decreases whereas over the same range of magnetic field electron temperature shows a minimum in a transverse magnetic field and then increases with the increase of magnetic field. Using the two fluid model of plasma an expression for the ratio of electron temperature with and without magnetic field has been deduced in a variable magnetic field which can explain the occurrence of maxima in case of axial magnetic field and minima in case of transverse magnetic field. The quantitative agreement between experimental results and analytical expression is to a certain extent satisfactory. The limitations of the analysis have been discussed.

Keywords : Arc plasma, two fluid model, electron temperature, axial and transverse magnetic field

PACS Nos. : 52.70.Ds, 52.80. Mg

1. Introduction

The investigation on the measurement of plasma parameters such as electron density, collision frequency of electrons with atoms and electron temperature and their variation with pressure, discharge current and external magnetic fields has been extensively investigated by the standard plasma diagnostic techniques in case of glow discharge but the corresponding data for arc plasma has been little reported so far. For the last few years we have taken up a systematic investigation of the properties of arc plasma [1-9]. The aim of these investigations is to develop a consistent theory for the occurrence of arc plasma and to study the transition phase from glow discharge to arc plasma. In a recent communication [10] we have shown how the electron density and electron temperature in an arc plasma can be measured by Langmuir single probe method. It is well known that in the positive column of a glow discharge or in an arc plasma, a radial electric field develops as a result of net charge separation due to different rates of diffusion of ions and electrons (ambipolar diffusion). Sen, Ghosh and Ghosh [6] evaluated the electron temperature in glow discharge in air (pressure 1 torr) from the measurement of diffusion voltage taking the radial profile of charge distribution as Bassalian. They also measured the variation of electron temperature in a magnetic field by placing the discharge tube in a transverse magnetic field (0 to 100 G). The utilization of this method in case of arc plasma will be investigated in the present work taking into account the radial distribution of charged particles in an arc plasma as has been provided by Ghosal *et al* [3]. Further the theoretical analysis carried out by Allis and Allen [11], Tonks and Allis [12] and Huxlay [13] show that the behaviour of the electrons and consequently electron temperature, the radial distribution of electrons, the current voltage characteristics and other properties will be different when the external magnetic field is transverse than when the field is axial. The results obtained by Sen and Das [1] indicate that the theoretical expression deduced by Beckman [14] and later on simplified by Sen and Gupta [15] regarding the variation of electron density and electron temperature in a transverse magnetic field in glow discharge is valid in the case of arc plasma as well. Further it has been observed by Sen and Gantait [9] that the voltage current characteristics undergo a similar change for both the alignments of magnetic field but the transverse magnetic field has a more dominant effect on the properties of arc plasma than that of an axial magnetic field. Hence in the present investigation it is proposed to evaluate the electron temperature in an arc plasma by measuring the diffusion voltage and study its variation in both transverse and axial magnetic fields and provide a theoretical analysis of the observed results.

2. Experimental arrangement

For investigation in an arc plasma a mercury arc has been utilized. For measurement of diffusion voltage in transverse magnetic field the arc tube of 41 cm length, 26.5 cm anode-cathode spacing, 2.2 cm inner diameter and 2.5 cm outer diameter was used and in case of axial magnetic field the arc tube is of 9.1 cm length, 6.2 cm anode-cathode spacing, 1.86 cm inner diameter and 2.16 cm outer diameter. Both the arc tubes are made of pyrex glass. The arc is excited between two mercury pool electrodes (fitted with two tungsten wires for external electrical connection) by a 250 V d.c. source from a generator with a rheostat to control the current as recorded by an ammeter. The whole arc system is cooled by air coolers and two mercury pool electrodes by circulation of water. To maintain the pressure constant in the tube, dry air which acts as a buffer gas has been introduced by a variable microleak of a needle valve fitted in the vacuum arrangement. The pressure has been measured by a calibrated pirani gauge. For measurement of parameters in transverse magnetic field the portion of the positive column of the arc has been placed between the pole pieces of an electromagnet while for that in longitudinal magnetic field the whole arc tube has been inserted between the two pole pieces.

The electromagnets have been run by a stabilised d.c. power supply (Type EM20), and the magnetic field has been calibrated by a Gauss meter (Model G14). After every sequence of measurement the electromagnet is suitably demagnetised.

For diffusion voltage measurement in transverse magnetic field two cylindrical probes (tungsten) of 0.8 cm length and 0.014 cm radius have been inserted parallel to one another, one along the axis $r = 0$ and the other at a distance of 0.6 cm from the axis in the same cross sectional plane of the tube. But these two probes in case of axial magnetic field are of 0.53 cm in length while other specifications are the same as in transverse magnetic field. In the above two cases the output voltage at the two probes has been measured by a VTVM having an internal impedance of 100 MΩ. A low pass filter circuit has been provided at the output of the probes to prevent oscillation generated in the arc from reaching the VTVM, which records the magnitude of the diffusion voltage. The diffusion voltage has been measured as a function of the magnetic field with arc current as a parameter. Specifically for transverse magnetic field, the diffusion voltage has been measured upto the magnetic field of 1000 Gauss at three constant arc currents namely 2.5 A, 3.0 A and 3.5 A and in axial magnetic field upto 1010 Gauss at three fixed arc currents namely 3.0 A, 4.0 A and 5.0 A.

3. Results and discussion

3.1. In transverse magnetic field :

The variation of diffusion voltage has been plotted in Figure 1 for magnetic field varying from zero to 1.0 KG. It is observed that the diffusion voltage increases with magnetic field for

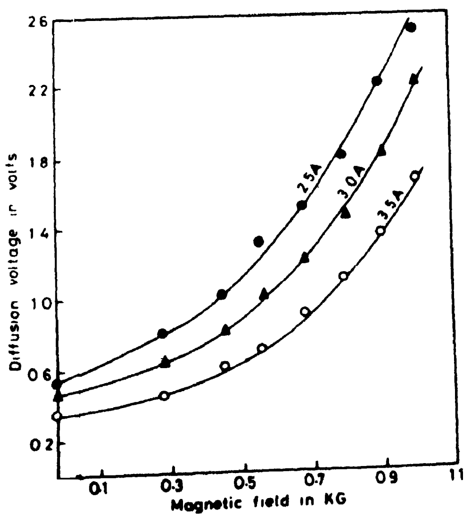

Figure 1. Variation of diffusion voltage with magnetic field for different arc currents (transverse magnetic field).

three fixed currents namely 2.5 A, 3.0 A and 3.5 A. The values of diffusion voltage are entered in Table 1 for values of magnetic field used in the experiment. From the nature of the curves it can be assumed that an empirical relation of the form $V_{RH} = V_R\,[1 + m' H^2]$ where V_{RH} and V_R are the diffusion voltages with and without magnetic field and m' is a constant can represent the experimental results. We can estimate the value of m' by a statistical method, which is shown for a current of 2.5 A.

Table 1. Diffusion voltage for different magnetic field.

Magnetic field in K Gauss	Arc current = 2.5 A		Arc current = 3.0 A		Arc current = 3.5 A	
	V_{RH} (exp)	V_{RH} deduced from eq. (1)	V_{RH} (exp)	V_{RH} deduced from eq. (1)	V_{RH} (exp)	V_{RH} deduced from eq. (1)
0.28	0.80	0.7075	0.65	0.6091	0.45	0.4562
0.45	1.00	0.9568	0.80	0.8134	0.60	0.6086
0.56	1.30	1.1807	1.00	0.9963	0.70	0.7450
0.68	1.50	1.4789	1.20	1.2413	0.90	0.9277
0.80	1.80	1.8357	1.45	1.5337	1.10	1.1458
0.90	2.20	2.1772	1.80	1.8137	1.35	1.3545
1.00	2.50	2.5590	2.20	2.1265	1.65	1.5878

$$V_{RH} = V_R[1+m'H^2]$$

$$S = \sum\left[V_{RH} - V_R - m'V_R H^2\right]^2$$

$$\frac{dS}{dm'} = -2\sum\left[V_{RH} - V_R - m'V_R H^2\right]V_R H^2 = 0$$

$$\sum_{i=1}^{i=7} V_{RH}H^2 = V_R\sum_{i=1}^{i=7} H^2 + m'V_R\sum_{i=1}^{i=7} H^4$$

$$m' = \frac{\sum_{i=1}^{i=7} V_{RH}H^2 - V_R\sum_{i=1}^{i=7} H^2}{V_R\sum_{i=1}^{i=7} H^4}$$

$V_R = 0.55$ Volts $\qquad \sum V_{RH}H^2 = 6.8005.$

$\sum H^2 = 3.5069 \qquad \sum H^4 = 2.425.$

$$m' = \frac{6.8005 - 1.928}{1.3338}$$

$$= 3.6526.$$

(refer Table 1)

The value of m' for arc currents of 3.0 A and 3.5 A has also been estimated and found to be 3.43021 and 3.41062 respectively. To verify whether the assumed empirical relation for V_{RH} agree with experimental results the calculated values of V_{RH} are compared with experimental results in Table 1 for three arc currents. It is evident from this table that the results are in good agreement with each other. Hence, we can conclude that the variation of diffusion voltage in a transverse magnetic field can be represented as

$$V_{RH} = V_R\,(1 + \acute{m}\,H^2) \tag{1}$$

where the value of $\acute{m}$ decreases with increase of arc current. We now proceed to show how the values of electron temperature with and without magnetic field can be evaluated from the measured values of diffusion voltage.

In glow discharge the radial distribution profile of charged particle density has been taken to be Basselian. It has however, been shown by Ghosal *et al* [3] that the radial distribution function for the azimuthal conductivity for an arc plasma is of the form

$$\sigma_r = \sigma_0\left[1 - \frac{r^2}{R^2}\right]^n \tag{2}$$

where σ_0 is the on axis conductivity, σ_r is the conductivity at a distance r from the axis of the tube, R is the arc tube radius and n is a constant which has been shown to be

$$n = \left[\frac{R^2}{a'} - 2\right]$$

where a' is an experimentally measured quantity that changes with arc current. It has been shown by Sen *et al* [6] that the diffusion voltage V_R is

$$V_R = -\int \frac{dn_e}{n_e}\,\frac{KT_e}{e} \tag{3}$$

and as the electron density is proportional to conductivity we can write from eq. (2)

$$n_e = n_0\left[1 - \frac{r^2}{R^2}\right]^n . \tag{4}$$

Beckman [14] has deduced that in presence of transverse magnetic field, the radial electron density is decreased, Sen and Gupta [15] have shown that Beckman's expression can be stated as

$$n_{eH} = n_e \exp(-aH) \tag{5}$$

where n_{eH} and n_e are the electron concentrations in the presence of and in absence of magnetic field respectively, and

$$\lambda\Omega_r \tag{6}$$

where E is the axial voltage drop per unit length, and

$$C_1 = \left(\frac{e}{m}\right)^2$$

where L is the mean free path of the electrons at a pressure of 1.0 torr, K the Boltzman constant, T_e the electron temperature, v_r the random velocity of electrons and r is the distance of the second probe from the probe at tube axis and P is the vapour pressure of mercury.

Hence, in presence of magnetic field we get from eq. (3)

$$V_{RH} = -\int \frac{dn_{eH}}{n_{eH}} \frac{KT_{eH}}{e},$$

and with the help of the eqs. (4) and (5) it follows that

$$V_{RH} = -\frac{KT_{eH}}{e} \int_{(n_{eH})_0}^{(n_{eH})_r} \frac{d\left\{n_0\left(1-\frac{r^2}{R^2}\right)^n \exp(-aH)\right\}}{n_0\left(1-\frac{r^2}{R^2}\right)^n \exp(-aH)}$$

$$= \frac{-KT_{eH}}{e}\left[n \log\left(1-\frac{r^2}{R^2}\right) - aH\right].$$

Hence,

$$T_{eH} = \frac{e}{K} \cdot \frac{V_{RH}}{\left(2n \log \frac{R}{\sqrt{R^2-r^2}} + aH\right)}, \tag{7}$$

and when H = 0 it reduces to

$$T_e = \frac{e}{K} \cdot \frac{V_R}{2n \log \frac{R}{\sqrt{R^2-r^2}}}. \tag{8}$$

From eqs. (7) and (8)

$$\frac{T_{eH}}{T_e} = \frac{V_{RH}}{V_R} \frac{2n \log \frac{R}{\sqrt{R^2-r^2}}}{\left[2n \log \frac{R}{\sqrt{R^2-r^2}} + aH\right]}$$

Putting the value of V_{RH} from eq. (1)

$$\frac{T_{eH}}{T_e} = \left(1+m'H^2\right)\frac{X}{X+aH}$$

where

$$X = 2n \log \frac{R}{\sqrt{R^2 - r^2}}$$

and

$$\frac{T_{eH}}{T_e} = \frac{1 + \acute{m}H^2}{1 + \frac{aH}{Y}}. \tag{9}$$

Therefore, with the values of $\acute{m}$ and $\frac{a}{X}$ from eq. (9) $\frac{T_{eH}}{T_e}$ can be estimated for different values of H.

In the present investigation the value of 'a' given in the expression (6) has been estimated for three arc currents, when arc current is 2.5 A, with E = 37/26.5 volts/cm., r = 0.6 cm, $C_1 = 2.0 \times 10^{-6}$, P = 0.3731 torr (from an earlier paper [5] and T_e = 10131°K [10], the value of 'a' becomes 1.83×10^{-3} while for 3.0 A and 3.5 A arc currents it becomes 1.013

$\times 10^{-3}$ and 0.937×10^{-3} respectively taking the corresponding values of the above quantities. And the value of $X = 2n \log \quad ;$ can easily be calculated with the knowledge of quantitative value of n. Some values for n were obtained by Ghosal *et al* [3], but a measurement of n for a wider range of current (2.2 A to 5.0 A) has been performed in this laboratory by Gantait [16]. Some of these values have been taken to calculate the value of X. The plotting of n with arc current has been reproduced in Figure 2.

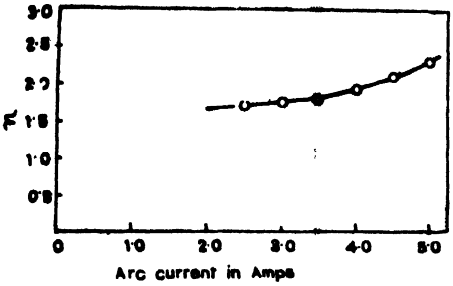

Figure 2. Variation of n with arc current.

With n = 1.7149, 1.7446 and 1.8158 the value of X_1 is found to be 0.60707, 0.61759 and 0.64279 for arc currents 2.5 A, and 3.5 A respectively (R, the inner tube radius = 1.1 cm and r, the separation between the two probes = 0.6 cm). Therefore putting these values in eq. (9), the values of $\frac{T_{eH}}{T_e}$ have been calculated and the results plotted in Figure 3. Each curve shows a minimum around 200–300 Gauss of magnetic field.

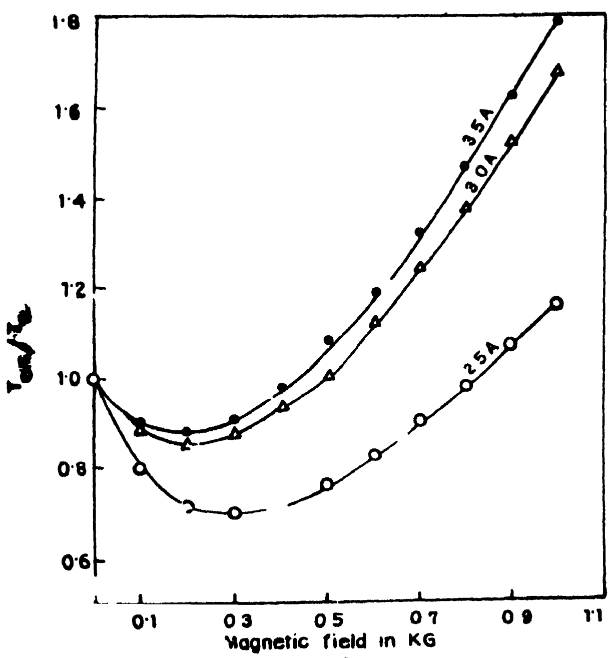

Figure 3. Variation of T_{eH}/T_e with magnetic field (magnetic field transverse).

3.2. Axial magnetic field:

In case of axial magnetic field it has been shown by Sen and Gantait [9] that the conductivity of an arc plasma can be represented by

$$\sigma_H = \sigma_0 \exp(-\alpha H)$$

where σ_H and σ_0 are the conductivities with and without magnetic field and the values of α have been calculated for the three arc currents 3, 4 and 5 amp by the statistical method. Hence in case of axial magnetic field we can write that

$$n_{eH} = n_e \exp(-\alpha H)$$

and it can be shown as in eq. (9)

$$\frac{T_{eH}}{T_e} = V_{RH}\,\frac{2n\log\dfrac{R}{\sqrt{R^2-r^2}}}{2n\log\dfrac{R}{\sqrt{R^2-r^2}}+\alpha H} \tag{10}$$

The values of V_{RH} in axial magnetic field as measured experimentally have been plotted against the corresponding values of the magnetic field in Figure 4. The values of α as provided by Sen and Gantait [9] are 0.2859, 0.2744 and 0.2714 respectively for three arc currents 3 A, 4 A and 5A.

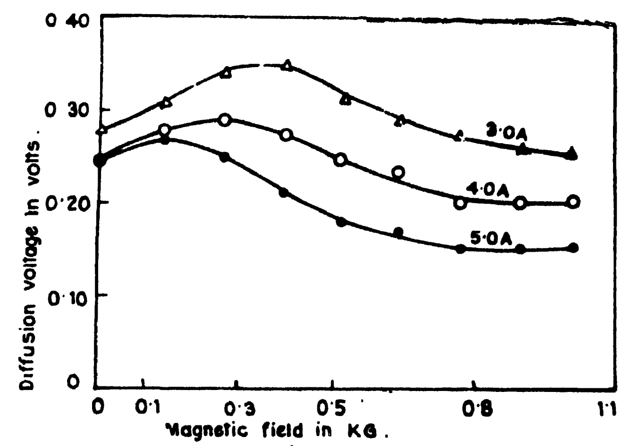

Fig. 4.

Figure 4. Variation of diffusion voltage with magnetic field (axial magnetic field).

The values of $\frac{T_{eH}}{T_e}$ calculated from eq. (10) have been plotted against magnetic field in Figure 5. A comparison with the results entered in Figure 3 for transverse magnetic field shows that whereas in case of transverse magnetic field, a minimum is observed for $\frac{T_{eH}}{T_e}$ for all the three arc currents, a maximum in the value of $\frac{T_{eH}}{T_e}$ is observed for axial magnetic field almost in the same region of magnetic field. After attaining the minimum value T_{eH} increases almost linearly with the magnetic field when it is transverse whereas it decreases with magnetic field when the magnetic field is axial.

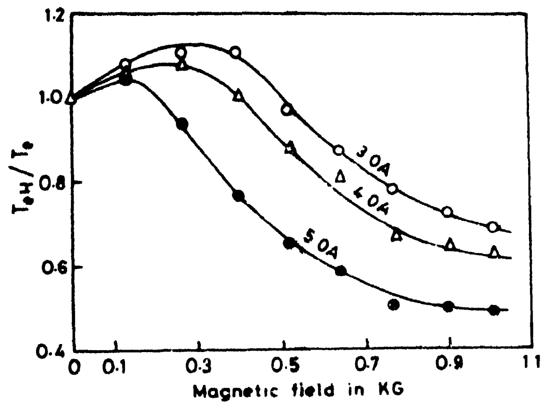

Figure 5. Variation of $\frac{T_{eH}}{T_e}$ with magnetic field (magnetic field axial)

In a two-fluid model we may assume that two distinct temperatures T_e (for electron) and T_g (for gas) exist. The difference between these two temperature can be derived from an energy balance equation leading to

$$\frac{T_e - T_g}{T_e} = \frac{\pi m_g}{24 m_e} \cdot \frac{\lambda_e^2 E^2 e^2}{K^2 T_e^2}$$

where symbols have their usual significance [17]. It follows that

$$T_e\left(T_e - T_g\right) = C\lambda_e^2 E^2 \tag{11}$$

where

$$C = \frac{\lambda m_g e^2}{24 m_e K^2} \cdot$$

In presence of magnetic field, eq. (11) can be modified as

$$T_{eH}\left(T_{eH} - T_g\right) = C\lambda_{eH}^2 T_{eH}^2 \tag{12}$$

From eqs. (11) and (12) we get

$$\left(T_{eH} - T_e\right)\left(T_{eH} + T_e - T_g\right) = C\left[\lambda_{eH}^2 T_{eH}^2 - \lambda_e^2 T_e^2\right]$$

with approximation that $T_e + T_{eH} \approx 2T_e$

$$\frac{T_{eH}}{T_e} - 1 \,| = \frac{}{T_e^2 \left| 2 - \frac{T_g}{T_e} \right.} \cdot \left[\lambda_{eH}^2 E_{eH}^2 - \lambda_e^2 E^2\right] \tag{13}$$

It has been deduced by Sen and Gantait [9] that in presence of magnetic field $E_H = E(1 + nH)$ and $\lambda_{eH} = \dfrac{\lambda_e}{1+C_1 H^2}$ [18,19].

where C_1 is the same constant as introduced in eq. (6). Eq. (13) can further be simplified as

$$\frac{T_{eH}}{T_e} = 1+\beta\left[\frac{m^2H^2 + 2mH - C_1\dfrac{H^2}{P^2}}{1+C_1\dfrac{H^2}{P^2}}\right]$$

where

$$\beta = \frac{CE^2\lambda_e^2}{T_e^2\left[2-\dfrac{T_g}{T_e}\right]}.$$

Then

$$\frac{1}{T_e}\cdot\frac{dT_{eH}}{dH} = \frac{\beta\left[mC_1\dfrac{H^2}{P^2} - \left(m^2 - \dfrac{C_1}{P^2}\right)H - m\right]}{1+C_1\dfrac{H^2}{P^2}} = 0.$$

Hence,

$$H = \frac{\left(m^2 - \dfrac{C_1}{P^2}\right) + \sqrt{m^4 + \dfrac{C_1^2}{P^4} + 2m^2\dfrac{C_1}{P^2}}}{2mC_1 / P^2} \tag{14}$$

with simplification

$$H = \frac{m}{C_1/P^2}.$$

In order to find whether the value of H corresponds to minimum or maximum, eq. (14) has been differentiated again so as to yield

$$\frac{1}{T_e}\frac{d^2T_{eH}}{dH^2} = \frac{-2\beta}{\left(1+C_1\dfrac{H^2}{P^2}\right)^3}\left[\left(1+C_1\frac{H^2}{P^2}\right)\left\{2mC_1\frac{H}{P^2} + \frac{C_1}{P^2}m^2\right\}\right.$$

$$\left. - \left\{mC_1\frac{H^2}{P^2} + \left(\frac{C_1}{P^2} - m^2\right)H - m\right\}4C_1\frac{H}{P^2}\right].$$

Putting the value of $H = \dfrac{m}{C_1/P^2}$ in eq. (15)

$$\frac{1}{T_e}\frac{d^2T_{eH}}{dH^2} = 2\beta\left[m^2 - \frac{C_1}{P^2} + \frac{m^4p^2}{C_1} + \frac{m^6p^4}{C_1^2} + \cdots\right].$$

In case of axial magnetic field, $m = 0.295 \times 10^{-3}$ [9] and $C_1 = 0.125 \times 10^{-6}$ [5] (Sadhya and Sen, 1980) and we have

$$\frac{1}{T_e}\frac{d^2T_{eH}}{dH^2} = 2\beta\left[0.087\times10^{-6} - 1.358\times10^{-7} + 5.4\times10^{-9} + \cdots\right]$$

$$= \text{negative quantity}$$

In case of transverse magnetic field, $m = 5.55 \times 10^{-3}$ and $C_1 = 2.8 \times 10^{-6}$ [1] and we have

$$\frac{1}{T_e}\frac{d^2T_{eH}}{dH^2} = 2\beta\left[30.8\times10^{-6} - 30.4\times10^{-6}\right.$$
$$\left.+31.15\times10^{-6} + 970.3\times10^{-6} + \cdots\right.$$
$$= \text{a positive quantity.}$$

We can thus conclude that in case of an axial magnetic field a maximum in the value of T_{eH} whereas in case of transverse magnetic field a minimum in the value of T_{eH} is expected when the magnetic field is varied. Two experimental results support these theoretical deductions.

Further, the values of H_{max} where the electron temperature becomes a maximum in the axial magnetic field and the values of H_{min} where electron temperature becomes a minimum in a transverse magnetic field, have been calculated for three different arc currents from the respective values of m and C_1 and the results entered in Table 2. The corresponding values of mercury vapour pressure have been taken from the earlier paper by Sadhya and Sen [5].

Table 2. Calculated and experimental values of H_{max} and H_{min} in axial and transverse magnetic field.

Arc current in amps.	H_{max} (exp) K Gauss	H_{max} (calculated) K Gauss
3.0	0.310	0.3285
4.0	0.200	0.2818
5.0	0.142	0.2010
	Transverse magnetic field	
	H_{min} (Expt.) (K Gauss)	H_{min} (Calc.) (K Gauss)
2.5	0.288	0.2735
3.0	0.201	0.1810
3.5	0.188	0.1320

The quantitative agreement between the experimental and calculated values is not very satisfactory as is to be expected due to some uncertainty in the values of C_1 which is the square of the mobility of the electrons at a pressure of one torr. There is lack of experimental data in literature regarding the mobility of electrons in mercury vapour but the order of magnitude of C_1 is of the right order as is found in McDaniel [20]. However, the agreement between the experimental and calculated values of H_{max} or H_{min} is of the right order of magnitude.

Starting with the expression for electron temperature which is derived by considering the arc plasma as a two fluid system it has been possible to derive an expression for variation of electron temperature with magnetic field and we find that the theory predicts that in an axial field electron temperature becomes a maximum at a certain magnetic field and then decreases whereas it shows a minimum and then increases with magnetic field when the field is transverse. The experimental results confirm the validity of the theory. Further, the values of electron temperature calculated from diffusion voltage measurements and assuming the radial distribution of charged particles in an arc plasma as provided by Ghosal *et al* [3] give the correct order of magnitude for electron temperature thereby proving the validity of the proposed radial distribution function and the measurement of diffusion voltage in an arc plasma can be an alternative diagnostic tool for measurement of electron temperature. As has been noted by Franklin [21], electron temperature decreases with the axial magnetic field for higher values of magnetic field in glow discharge and similar results have also been obtained in the present investigation on arc plasma with the exception that for smaller values of magnetic field a maximum in the value of T_{eH} has been found In transverse magnetic field, the electron temperature increases with higher values of magnetic field after attaining a minimum for smaller values of magnetic field.

References

[1] S N Sen and R P Das 1973 *Int. J. Electron.* **34** 527

[2] S K Ghosal, G P Nandi and S N Sen 1976 *Int. J. Electron.* **41** 509

[3] S K Ghosal, G P Nandi and S N Sen 1978 *Int. J. Electron.* **44** 409

[4] S K Ghosal, G P Nandi and S N Sen 1979 *Int. J. Electron.* **47** 415

[5] S K Sadhya and S N Sen 1980 *Int. J. Electron.* **49** 235

[6] S N Sen, S K Ghosh and B Ghosh 1983 *Indian J. Pure Appl. Phys.* **21** 613

[7] S N Sen, S K Sadhya, M Gantait and D C Jana 1987 *Int. J. Electron* **63** 55

[8] S N Sen and M Gantait 1987 *Indian J. Pure Appl Phys.* **25** 165

[9] S N Sen and M Gantait 1988 *Pramana -J. Phys.* **30** 143

[10] S N Sen, M Gantait and C Acharyya 1989 *Indian J Pure Appl Phys* **27** 220

[11] W P Allis and H W Allen 1937 *Phys. Rev.* **52** 703

[12] L Tonks and W P Allis 1937 *Phys. Rev.* **52** 710

[13] L G H Huxley 1937 *Phil. Mag.* **23** 210

[14] L Beckman 1948 *Proc. Phys. Soc.* **61** 515

[15] S N Sen and R N Gupta 1971 *J. Phys.* **D4** 510

[16] M Gantait 1988 *PhD Thesis* (North Bengal University, Darjeeling, India)

[17] M N Hirsh and H J Oskam 1978 *Gaseous Electronics* Vol. 1 (New York : Academic)

[18] H A Blevin and S C Haydon 1958 *Aust. J. Phys.* **11** 18

[19] S N Sen and A K Ghosh 1963 *Canad. J. Phys.* **41** 613

[20] E W Mcdaniel 1964 *Collision Phenomena in Ionised Gases* (New York : John Wiley)

[21] R N Franklin 1976 *Plasma Phenomena in Gas Discharge* (Oxford : Clarendon)